NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

SATELLITE CONSTELLATION OPTIMIZATION FOR TURKISH ARMED FORCES

by

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March 2013

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704–0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 2013	Master's Thesis

4. TITLE AND SUBTITLE
SATELLITE CONSTELLATION OPTIMIZATION FOR TURKISH ARMED FORCES

5. FUNDING NUMBERS

6. AUTHOR(S) Huseyin Kiremitci

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943–5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

Advancing technologies in smallsats provide remote sensing and communications capabilities achievable with a constellation of satellites at a reasonable cost to meet military needs. Like any other nation looking for a cheap but effective solution in that area, Turkey might also benefit from a replacement of its remote sensing assets. Currently Turkish Armed Forces rely on a limited number of reconnaissance aircraft and Unmanned Aerial Vehicles, which do not provide real-time or near real-time remote sensing capabilities. Near real-time remote sensing needs for the Turkish warfighter dictates Turkish Armed Forces reach that capability as soon as possible. Likewise, replacing its conventional communication radios with satellite communication devices would also fulfill warfighter needs. While current communication devices have physical limitations in Turkey's mountainous terrain and the surrounding seas, satellite communication capability would provide wider coverage and for specific frequencies might provide better resistance to jamming and interference too. For the benefit of Turkish Armed Forces communications needs, a satellite constellation must be optimized such that effective coverage will be achieved with the least number of satellites to provide a reasonable cost. In this study, Satellite constellation optimization for the Turkish Armed Forces will be achieved by using Analytical Graphics, Inc.'s Systems Tool Kit software for simulation and analysis of several possible communications and remote sensing satellite constellations covering Turkish territory and surrounding seas.

14. SUBJECT TERMS Satellite Constellation Optimization, Small Satellites, Turkey's Space Activities, Communication Satellites

15. NUMBER OF PAGES 69

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UU

NSN 7540–01–280–5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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SATELLITE CONSTELLATION OPTIMIZATION FOR TURKISH ARMED FORCES

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

NAVAL POSTGRADUATE SCHOOL
March 2013

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ABSTRACT

Advancing technologies in smallsats provide remote sensing and communications missions achievable with a constellation of satellites at a reasonable cost for the military needs. Like any other nation looking for a cheap but effective solution in that area, Turkey might also benefit from a replacement of its remote sensing assets. Currently, Turkish Armed Forces rely on limited number of reconnaissance aircraft and Unmanned Aerial Vehicles, which do not provide real-time or near real-time remote sensing capabilities. Near real-time remote sensing needs for the Turkish warfighters dictates Turkish Armed Forces to reach that capability as soon as possible. Likewise, replacing its conventional communication radios with satellite communication devices would also fulfill the warfighter needs. While current communication devices have physical limitations in Turkey's mountainous terrain and the surrounding seas, satellite communication capability would provide a wider coverage and for specific frequencies it might provide a better resistance to jamming and interference too. For the benefit of Turkish Armed Forces communications needs, a satellite constellation can be optimized such that an effective coverage will be achieved with the least number of satellites for providing a reasonable cost. In this study, Satellite constellation optimization for Turkish Armed Forces will be achieved by using Analytical Graphics, Inc.'s Systems Tool Kit software for simulation and analysis of several possible communications and remote sensing satellite constellations covering Turkish territory and surrounding seas. The Concept of Operations (CONOPS) for a smallsat constellation will be described and an optimized smallsat constellation will be modeled using STK software. The resulting data will be analyzed and discussed in the form of a recommendation that would benefit the Turkish Armed Forces.

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LIST OF ACRONYMS AND ABBREVIATIONS

AGI	Analytical Graphics, Inc.
C2	Command and Control
COMMS	Communications
COTS	Commercial Off-the-Shelf
CUBESAT	Cube Satellite
GEO	Geostationary Earth Orbit
HQ	Headquarter
ISR	Intelligence Surveillance and Reconnaissance
LEO	Low Earth Orbit
METU	Middle East Technical University, Ankara, TURKEY
MIT	Massachusetts Institute of Technology, Cambridge, MA
NPS	Naval Postgraduate School, Monterey, CA
R&D	Research and Development
SMALLSAT	Small Satellite
STK	Satellite Took Kit
TAI	Turkish Aerospace Industries, Inc.
TDMA	Time Division Multiple Access
TT&C	Telemetry, Tracking, and Command
TÜBİTAK	The Scientific and Technological Research Council of Turkey
TÜBİTAK UZAY	Space Technologies Research Institute
UAV	Unmanned Aerial Vehicle

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ACKNOWLEDGMENTS

I express sincere appreciation to Lieutenant Colonel J. Scott Matey (U.S. Army) for his guidance, assistance and insight throughout the research. I would like to thank Captain Alan Scott (U.S. Navy, Retired) and Prof. Charles M. Racoosin for their guidance and suggestions during the lectures and thesis. I would also like to offer exceptional thanks to Naval Postgraduate School Space Systems Academic Group and AGI Software Inc. for their technical assistance and lectures. And a lot of thanks to my lovely wife, Deniz Kiremitci, for all your support, patience and faith in me.

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DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Republic of Turkey, the Turkish Armed Forces, the Turkish Land Forces, the Turkish Naval Forces or the Turkish Air Force.

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I. BACKGROUND

Figure 1. Geographical map of Turkey.[1]

Turkey's territory has two unique structural properties that create a very complex terrain structure, which negatively affects the quality and range of terrestrial communication systems and subsequently decreases the effectiveness of the Turkish Armed Forces in providing security both in the country and the region. First, Turkey has a very rough and mountainous land surface, especially in the eastern part of the country. This rugged landmass is physically insufficient for broadcasting terrestrial communication signals over long distances without interference due to obstruction of the signal path. Second, Turkey has a very long coastline surrounded by four seas in almost three directions around the country, which creates a necessity for the Turkish Armed Forces to obtain good communications over these seas. Both this mountainous territory and the seas around it create a challenging environment for the Turkish Armed Forces while also protecting and defending the country against external threats, particularly the terrorist activities occurring mostly in the eastern part of the country since the 1980s. In order to strengthen the Turkish Armed Forces' effectiveness, assist

[1] From Analytical Graphics, Inc.'s Systems Tool Kit Software, Version 9.2.2, 2011.

combat operations in the war against terror, improve the security of both the country and the region, and to improve the security of the North Atlantic Treaty Organization's (NATO) eastern front, there is a crucial need for better communications and better remote sensing capabilities over Turkish territory and the surrounding seas.

The Republic of Turkey is a large and roughly rectangular peninsula situated between southeastern Europe and Asia.[2] Functioning as a bridge between these two continents throughout history, Turkey extends more than 1,600 kilometers from west to east and 800 kilometers from north to south with a total land area of 779,452 square kilometers.[3] Nearly 85 percent of the land is at an elevation of at least 450 meters, whereas the median altitude of the country is 1,128 meters.[4] More than 80 percent of the land surface is rough, broken and mountainous. This rough terrain negatively affects quality and range of communications especially in the eastern part of the country, where this ruggedness is accentuated between two folded mountain ranges with a median elevation of more than 1,500 meters.[5] The eastern part of the country is also where Turkish Armed Forces have been fighting against the Kurdistan Workers Party (PKK)/Kurdistan Peoples' Congress (Kongra-Gel) terrorist organization since the 1980s. Small groups of PKK/Kongra-Gel terrorists mainly located in the mountains of northern Iraq, the south-west region of Iran and the south-east region of Turkey, often attack Turkish military and civilians (especially but not only) in the mountainous eastern part of the country, where they take advantage of this challenging environment and successfully escape abroad (back to Iranian and Iraqi territories) in most cases. To detect terrorist activities in the region, Turkish Armed Forces have been executing Intelligence Surveillance and Reconnaissance (ISR) missions with a limited number of UAVs and RF-4E

2 Helen Chapin Metz, "Turkey: A Country Study," *GPO for the Library of Congress*, 1995, http://countrystudies.us/turkey/18.htm.

3 Ibid.

4 Ibid.

5 Ibid.

Reconnaissance aircraft in its inventory. Due to the limited coverage these platforms can offer, the lack of continuous surveillance over the area, and the limited command and control range of UAVs, current ISR capabilities are insufficient to detect and track terrorist activity in this territory.

In addition to the complex structure of its terrain, the Turkish peninsula is also surrounded by four seas: the Mediterranean to the south, the Aegean to the west, the Sea of Marmara between the European and Asian land masses, and the Black Sea to the north.[6] The entire coastline spans more than 8,000 kilometers (approximately 5,000 miles) in length.[7] Protecting and defending the long coastline of Turkey mainly depends on better communications and surveillance capabilities that cover further distances over these seas in three directions (north, west and south). Quality communications between air and naval platforms over the surrounding seas are essential for joint operations to defend the country's territorial coastline. The interoperability of Turkish land, naval and air forces highly depends on the communication capabilities between the forces. Better surveillance and intelligence over these seas will provide the timely and effective response required to deter and oppose possible intruders.

Improving the security of Turkey will also benefit NATO. Since joining the alliance in 1952, Turkey has been an integral member, helping empower the defensive capabilities of the alliance on its eastern front. The improvement in the communications and remote sensing capabilities of the country will also boost NATO's capabilities in the region. Turkey is the eyes and ears of the alliance in the east. These space-based systems will provide better coverage not only over Turkish territory, but also will provide information about the places in non-NATO countries where these satellites fly over freely. Current capabilities of Turkey cannot provide ISR coverage over the denied territories. Living in the middle of such an unstable region as the Middle East, it is good for Turkey to know as

6 S. Sadi Seferoglu, "Turkey at a Glance," *Columbia University in the city of New York*, 20 April 2009, http://www.columbia.edu/~sss31/Turkiye/geo.html.

7 Ibid.

much as available about its neighbors in a timely manner, without causing any disputes related to the principle of sovereignty over airspace.

In addition to strengthening the Turkish Armed Forces' deterrence and capabilities, space-based capabilities will provide better support for border protection and fighting against illegal trafficking (for instance, human and arms trafficking) for the law enforcement forces of the country. The information obtained with these capabilities will help Turkish authorities detect any illegal trafficking on the land and over the seas around the country.

Better communication and remote sensing capabilities will improve the capabilities of the Turkish Armed Forces and NATO in their fight against terrorism and illegal trafficking, as well as enforcing the security of NATO and the region. The problem is fulfilling the need for better communications and remote sensing capabilities of Turkish Armed Forces especially in the mountainous terrain of the country and the surrounding seas (Black Sea, Aegean Sea and Mediterranean Sea). Potential solutions to this problem include developing new communications techniques, obtaining many communications relay stations over the peaks of mountains, using newer and more capable UAVs, or establishing high powered transmitters. However, this study focuses solely on examining a space-based solution in the form of a constellation of small satellites in LEO.

A. WHY SPACE?

Space-based capabilities offer many advantages, which motivates almost every nation in the world, including Turkey, to develop or acquire space technology, in spite of the magnitude of its cost, the high risk environment and the need for endless support it may require. As Jerry Jon Sellers described briefly in his book "Understanding Space: An Introduction to Astronautics," space offers a global perspective as the ultimate high ground, provides a clear view of the heavens without obscuring the atmosphere, enables development of advanced materials not possible on Earth under the gravitational force, has abundant resources like solar energy and extraterrestrial materials and is a

unique challenge as the final frontier.[8] Like any other country in today's world, these advantages are desirable for Turkey. Turkey wants to achieve the most advanced technology which is mainly available by improving its space technology and that will also benefit Turkey in its ultimate goal to become one of the most modern and influential societies in the world. Developing a constellation of satellites will be a significant step for Turkey. Therefore, a space related solution to the capability gaps of the Turkish Armed Forces will have indirect advantages that will help Turkey achieve all the advantages of space technology.

A space-based capability has two direct advantages for the Turkish Armed Forces: First, it provides more capabilities as the ultimate high ground, such as providing a wider perspective to see things globally rather than being limited to regional or local perspective. The coverage area on the ground increases as a satellite's orbital attitude increases, even though the payload technology (remote sensing or communications system) stays the same. The basic fundamentals of optics and waves state that the distance between the object (ground) and the focal point (either of the sensor or the antenna on a satellite or a flying platform) must increase in order to reach larger areas when executing remote sensing or communications missions. Flying at a higher altitude with the same sensor would provide a wider coverage area on the ground. For instance, it can take months to photograph the continental United States when using a camera on a jet aircraft in flight, however depending on the system properties, photographing the same area would only take days or weeks when using a satellite based remote sensor. The higher the altitude of the system, the less time it takes to cover the same amount of area on the ground, but at a lower resolution. The altitude can be increased to achieve the desired coverage up to where a resolution constraint permits or without any limitation when there is no resolution constraint at all.

Second, a space-based system provides the ability to fly over restricted territories when an aerial platform based remote sensing or communications

8 Jerry Jon Sellers, *Understanding Space, An Introduction to Astronautics Third Edition* (Air Force Academy, CO: McGraw Hill Companies Inc., 2005).

mission is not possible. A satellite can fly over any territory on Earth without regard to borders, denied territories, no fly zones or other restrictions. This advantage is unique to the space-based systems, and it is very beneficial especially for security related missions.

B. ADVANCING CAPABILITIES AND TECHNOLOGY OF SMALLSATS/CUBESATS

The latest developments in technology have significantly increased the capabilities of small satellites in recent years. Civil, commercial and military organizations have become more interested in smallsats as their costs are much lower than larger space systems.[9] Smallsats provide similar technology at a cheaper price, and more importantly they have the potential to be developed much more rapidly than larger satellites in a less complex structure.[10] The ability to quickly develop and deploy is the key competitive advantage for smallsats.[11]

Smallsats have existed since the beginning of the space age; however the current interest in smallsats resulted from two parallel development efforts.[12] The first development started in the 1970s at the University of Surrey in the United Kingdom (UK), when Martin Sweeting's team of engineers came up with the idea of using off-the-shelf components to build inexpensive satellites.[13] With these goals, University of Surrey Satellite-1 (UoSAT-1) was launched on 6 October 1981 from Vandenberg AFB (CA, USA), as a secondary payload.[14] It was placed into a 560 km, 3 am–3 pm sun-synchronous orbit (at 97.5 degrees inclination), on a mission to investigate and demonstrate the feasibility of the design,

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9 Jeff Foust, "*Emerging Opportunities for Low-Cost Small Satellites in Civil and Commercial Space,*" *24th Annual AIAA/USU Conference on Small Satellites,* 2010 (SSC10-IV-4).

10 Ibid.

11 Ibid.

12 Jeff Foust, "Smallsats on the Rise," *Space Quarterly Magazine*, December 17, 2012, URL: http://spaceref.biz/2012/12/smallsats-on-the-rise.html.

13 Ibid.

14 Surrey Satellite Technology U.S. LLC: "UoSAT-1: The Mission," 2013, http://www.sst-us.com/missions/uosat-1--launched-1981/uosat-1/uosat-1--the-mission.

construction, and launch of a scientific satellite at low cost within a budget of £250,000 and a 30-month timescale.[15] UoSAT-1 signals were heard, decoded, and analyzed by thousands of radio amateurs, schools, colleges, and universities around the world.

In April 1982, the satellite uplink was inadvertently blocked by the downlink, and commands could not be received until the problem was solved with assistance of the Stanford Research Institute (CA, USA) in September 1982. Although an orbital lifetime of 3.5 years was predicted, the satellite was operational for more than 8 years.[16] Despite the problems UoSAT-1 faced, it pioneered the cost effective "commercial off-the-shelf" (COTS) based small satellite boom. Most of these small satellites were built using donated materials and a homemade clean-room.[17] These early successes resulted in the formation of a company by the university with the name "Surrey Satellite Technology Ltd. (SSTL)" in 1985.[18] Since then, SSTL has developed increasingly sophisticated smallsats, and in 2008 The European Aeronautic Defense and Space Company (EADS) Astrium purchased the company from the university. The company continues to operate as an independent entity.[19]

The second effort started in 1990, when Jordi Puig-Suari, a professor at the California Polytechnic State University, and Bob Twiggs, a professor at Stanford University, designed a simple and inexpensive spacecraft which universities could afford to build and use as student projects.[20] They defined the term "CubeSat" as a spacecraft in the form of a cube with sides of ten

15 Ibid.

16 Ibid.

17 Surrey Satellite Technology U.S. LLC, "SSTL celebrates 30th anniversary of groundbreaking satellite UoSAT-1," October 06, 2011, http://www.sstl.co.uk/News---Events/2011-News-Archive?story=1899 under "News&Events."

18 Foust, "*Smallsats on the Rise.*"

19 Ibid.

20 Ibid.

centimeters and a mass of about one kilogram.[21] Although they were initially invented as student projects, CubeSats served in scientific research and technology demonstrations in so many projects that the “xU CubeSat” term became a standard measurement unit to define the size of a specific kind of small satellite. For instance, the popular “3U CubeSat” is created by combining three CubeSats together and forming a 30 cm x 10 cm x 10 cm satellite to create enough room for more components with increased capability.[22] As a result of these efforts, smallsats advanced to the point where they can now be developed with relatively modest resources: a small team of developers, off-the-shelf components, a limited test and development infrastructure, and a budget that is feasible and affordable for smaller organizations (especially those that are new to space technology development activities).[23]

Smallsats also present significant disadvantage due to their relatively shorter lifetime compared to larger satellites. Smallsats are typically launched into low earth orbit, and due to limited (or no) propulsion system capability, are unable to counter the force of drag and often reenter the atmosphere in less than a year. In addition, there are ongoing discussions about the legal, managerial and technical issues related to the operation of smallsats such as frequency coordination, registration of smallsats, management and operation of ground station networks, difficulties in finding affordable launch opportunities and increased space debris.[24] Satellites require the use of the radio frequency spectrum for communicating with ground-stations. The bandwidth and capacity of the spectrum is limited, so there is a need for smallsat developers to coordinate their frequency plans with other users in order to prevent harmful interference of

21 Ibid.

22 Ibid.

23 United Nations Committee on the Peaceful Uses of Outer Space, *Report on the third United Nations/Austria/European Space Agency Symposium on Small Satellite Programmes for Sustainable Development: Implementing small satellite programmes: technical, managerial, regulatory and legal issues*, (2011).

24 Ibid.

signals.[25] In addition to coordination of frequencies, as stated in UN resolutions, “Following the successful launch of a space object, launching states are required to register the satellite with the United Nations in line with General Assembly Resolution 1721 B (XVI) of 1961.” This provision includes smallsats and cubesats.[26] Although each sovereign country has the authority to make decisions on frequencies of terrestrial systems in their countries, they have to coordinate with other countries to prevent interference when making frequency allocation decisions for their space-based communications systems. This could impact the selection of their space systems equipment.

Another problem point is that the contact time of smallsats with ground stations is very small for any satellite orbiting at LEO, which creates a problem when downloading huge data packets such as a series of high-resolution imagery files.[27] The Education Office of the European Space Agency (ESA) developed the Global Educational Network for Satellite Operations (GENSO) with the idea of having a shared ground station network that allows a member smallsat to connect to several ground stations on the network to complete the required data transfer.[28]

The next problem area is related to the launch segment. The size, weight and shape of the smallsats present an advantage in lowering the financial cost of the launch. Unfortunately, no launch vehicles currently exist with a dedicated mission of propelling smallsats to LEO. Smallsats are treated as secondary payloads on current launch vehicles. Decisions on the launch date and time, orbit insertion altitude and method, location and orientation of the satellite inside the fairing and security and safety requirements are all made according to the primary payload requirements. That forces smallsat designers and operators to make a selection between waiting for the appropriate launch opportunity or

25 Ibid.

26 Ibid.

27 Ibid.

28 Ibid.

building a more sophisticated and over-engineered satellite that would be compatible with a less optimal launch vehicle or profile. Hoping to solve this problem, a smallsat consortium named “Canada-Europe-USA-Asia (CANEUS) International” proposed to build a global launch portal on the web to match small satellite developers with the launch vehicle providers.[29]

The last discussion point is that the recent boom in the development and deployment of smallsats will cause more space debris as these small sized spacecraft are hard to track and typically lack propulsion systems or other means to de-orbit after their missions end.[30] To overcome this problem there are several projects ongoing including the “CubeSail” concept of SSTL, which aims to de-orbit a smallsat with the help of extra drag created by deploying a sail at the end of satellite’s life.[31]

Increasingly capable small satellites have made space systems more affordable and accessible to a greater number of users in a growing number of countries.[32] The benefits of smallsats have led to an increased interest in maintaining basic capabilities in space technology development, even in developing countries and others that had previously been only users of space applications.[33] Turkey is one of the countries seeking to develop its space technology. Having limited resources and experience with space activities, an appropriate solution for Turkey would be to invest in smallsats in order to gain more significant space experience and technology in a shorter time period. The advantages of smallsats would contribute to the solution of the problem defined in “Chapter I Background” of this thesis. Warfighters of the Turkish Armed Forces require fast, reliable and affordable solutions which can be evolved in a timely

29 Ibid.

30 Foust, “*Emerging Opportunities for Low-Cost Small Satellites in Civil and Commercial Space.*”

31 Ibid.

32 (United Nations Committee on the Peaceful Uses of Outer Space 2011).

33 Ibid.

manner following research and experimentation. The advantages of developing smallsat constellations in support of the Turkish Armed Forces far outweigh the disadvantages.

C. POTENTIAL MISSIONS FOR SMALLSATS/CUBESATS

Highly beneficial speed and cost advantages of smallsats have caused increasing research, development and use of these systems in military science and technology, ISR, remote area communications, polling of unattended sensors, high resolution earth observation, and environmental (disaster) monitoring missions.[34] The National Aeronautics and Space Administration (NASA) is currently running several small satellite missions under its newly formed Small Spacecraft Technology Program. These missions include "PhoneSat 1.0 & 2.0" to demonstrate the use of Nexus S smart phone technology as the flight avionics for a small satellite, the "Edison Demonstration of SmallSat Networks (EDSN)" consisting of ten CubeSats in LEO to demonstrate space weather measurements, the "Integrated Solar Array and Reflect-array Antenna (ISARA) project demonstrating High-Bandwidth Communications by using its solar array as a reflector for the antenna, the project for "Optical Navigation and Communication with two CubeSats" and "Cubesat Proximity Operations Demonstration (CPOD)" where two 3U CubeSats demonstrate rendezvous, proximity operations, docking and servicing, and formation flight over a 1-year mission.[35] Other smallsat projects include:

- "Space Weather Network" a coordinated constellation of spacecraft to demonstrate distributed scientific measurement,
- "Made in Orbit" a smallsat kit assembled by the crew of the International Space Station (ISS),
- "Near Earth Object (NEO) Explorer" a network of microprobes to operate around an asteroid,

34 Foust, "*Emerging Opportunities for Low-Cost Small Satellites in Civil and Commercial Space.*"

35 Andrew Petro, "Small Spacecraft Technology," NASA Technology Days Presentation, 2012, http://www.nasa.gov/pdf/708647main_Small_Spacecraft_Tech_Day_Presentation.pdf.

- “Debris Remover” a spacecraft that can de-orbit inoperative satellites or debris,
- “Upper Atmosphere Swarm” a group of spacecraft to probe a volume of the upper atmosphere,
- “Satellite Inspector” or “Extravehicular Activity (EVA) Assistant” a spacecraft that can maneuver around another spacecraft to inspect and/or repair or assist an EVA astronaut or robot,
- “Mini X-Plane” a miniature test vehicle to research re-entry and landing,
- “Mini Return Capsule” a spacecraft to de-orbit and return sensitive payloads from ISS
- “Super A-Train” a constellation of 100 or more Earth Science satellites to provide continuous global data,
- “Planetary Omnibus” a large planetary spacecraft containing many small independent spacecraft to be released at the destination,
- “Self-Assembling Satellite” a satellite which autonomously assembles itself in orbit,
- “NEO Beacon” a beacon to be deployed to comets or other spacecraft to work as a “black box” and
- “Solar System Internet” a system to form a communications link from a spacecraft to the Internet.[36]

As Turkey is one of the countries trying to develop space technology in a timely manner, all of the above mentioned uses of smallsats will contribute to Turkey’s space technology research effort. The quick development and deployment of a smallsat into orbit greatly assists Turkey in gaining space experience. However, a prioritization should be made among those missions in order to fulfill urgent requirements of the country earlier than other less urgent or less necessary requirements. When we consider that the requirements of the Turkish Armed Forces are vital for the security of the country and are the most urgent ones at this time, the high priority missions are then “ISR and remote site communications.” Both space-based ISR and remote site communications

36 NASA, *2012 SmallSat Conference Presentation: NASA Town Hall Meeting*, Utah State University, August 13, 2012, http://www.nasa.gov/pdf/675932main_SmallSat_presentation_8_2012_Petro.pdf.

capabilities can enable gathering and sharing of required intelligence for Turkish Armed Forces to enforce security of the country and the region. Furthermore, Turkish space industry and technology can benefit from these assets during their design, manufacturing and operation processes. Beginning with the design, Turkish engineers will have a chance to research and test relevant techniques for communicating with space-based systems, design and manufacture space systems that can endure the space environment, develop software and processes for operating a space-based asset, maintain and operate remote sensing equipment and software and establish communications links between different force assets. Moreover, these activities can also help Turkey build an effective space program as well as a new administrative structure to run that program. For all of these reasons, it is in Turkey's best interest to start with a military-directed smallsat program which is quick to develop, easy to fund and less complex to run. In addition to these primary missions, it is possible to execute weather observation, environmental observation and disaster monitoring as secondary missions, as long as it is financially and physically feasible.

D. USERS/CUSTOMERS

The primary funding user and operator of the project will be The Turkish Armed Forces, which consists of The Turkish Air Force, Turkish Army, Turkish Navy, Turkish Gendarmerie, Turkish Coastguard, and Turkish Police Headquarters. In addition, all relevant Turkish government agencies including the Office of the President, Office of the Prime Minister, Ministry of Defense, Ministry of Interior Affairs and any other national security agency of the Turkish government would also benefit from this project. Finally, Turkey's allies and partners in NATO and other European countries would benefit from increased capability to prevent illegal trafficking along Turkish borders.

E. SELECTION OF MISSION

This thesis focuses on the problem defined in Chapter I Background section, which is to find a space-based solution to fulfill warfighters' needs. Therefore, the process for selection of the mission addressed in this thesis should follow these three steps: 1) examine Turkey's current space capabilities, 2) discuss the space-based capabilities that are required to overcome the problem stated in this thesis, and 3) select and define the mission that fulfills the gap between the current space-based capabilities and the required space-based capabilities.

Turkey's space studies and projects are coordinated by a publicly funded research institute named TÜBİTAK UZAY (Space Technologies Research Institute under The Scientific and Technological Research Council of Turkey) which was founded in 1985 with the signing of a protocol between the Middle East Technical University (METU) and The Scientific and Technological Research Council of Turkey (TÜBİTAK).[37] The institute specializes in space technologies, electronics, information technologies and related fields, while giving special emphasis to developing small satellite designs, manufacturing and testing satellite systems, leading Turkish Space Programs and initiating international collaboration in space technologies.[38] With efforts of the TÜBİTAK UZAY institute, Turkey has successfully launched three small satellite systems into LEO in the last decade. The first Turkish satellite, named BİLSAT-1, launched on 27 September 2003. The second, RASAT, was launched on 17 August 2011. The most recent launch, GÖKTÜRK-2, was successfully conducted on 18 December 2012. Turkey's space-based capability and experience continues to evolve in the areas of design, build and operations due to these small satellite programs.

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37 TÜBİTAK UZAY, General Information, (n.d.), http://www.uzay.tubitak.gov.tr/tubitakUzay/en/aboutUs/generalInfo.php under "About Us."

38 Ibid.

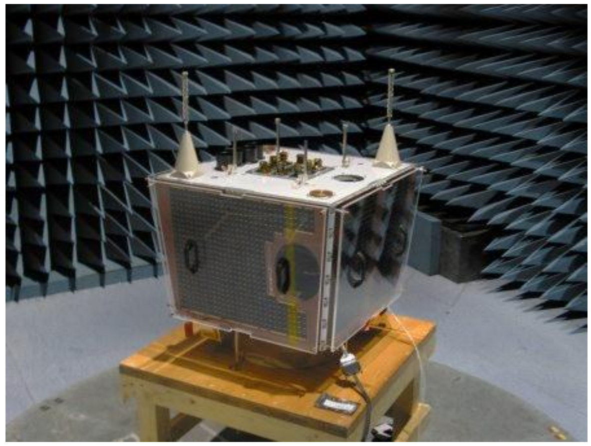

Figure 2. Photo of BILSAT-1.[39]

BILSAT-1, a remote sensing satellite, was designed and operated as part of the Disaster Monitoring Constellation (DMC). DMC is an international cooperative effort aimed at providing satellite images of any location in a possible disaster zone on Earth in less than 24 hours to assist International disaster relief and management organizations helping victims.[40] DMC member nations include the United Kingdom, Algeria, Nigeria and Turkey. BILSAT-1 carried five Earth observation cameras built in the United Kingdom (panchromatic, red, green, blue and near-infrared bands) and two additional payloads designed and built by Turkey. COBAN, a nine-band low resolution multi-spectral imager, and GEZGIN, a DSP based image processing module to compress images, were both designed and built by Turkish engineers in the context of the Know How Training and Transfer (KHTT) program that ran in parallel with the BILSAT project.[41]

39 SSTL, "BILSAT-1: Mission," (n.d.), http://www.sstl.co.uk/Missions/BILSAT-1--Launched-2003/BILSAT-1/BILSAT-1--The-Mission under "Missions."

40 TÜBİTAK UZAY, "TÜBİTAK UZAY Releases First Images from BİLSAT-1," October 9, 2003, http://www.uzay.tubitak.gov.tr/bilsat/en/news_archive/0001.asp under "News Archive."

41 SSTL, "BILSAT-1:Mission."

BILSAT-1 can no longer store energy on board and operations have been terminated since August 2006, after two of the cells of the battery reached their end of life.[42]

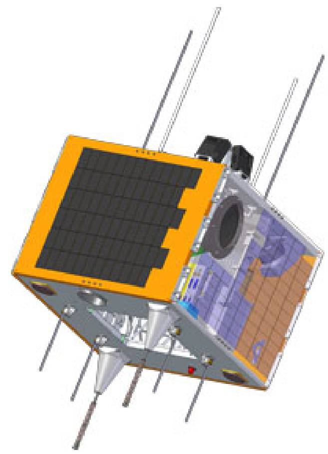

Figure 3. Photo of RASAT satellite.[43]

RASAT, the first micro satellite designed and built in Turkey, is an earth observation satellite with 7.5 meter panchromatic and 15 meter multispectral resolution capability.[44] GÖKTÜRK-2 is also an earth observation satellite, with 2.5 meter panchromatic and 5 meter multispectral resolution with a dual use mission (civil and military).[45] GOKTURK-2 provides data for disaster management, emergency situations, environmental control, mapping and planning, land cover survey, geology, coastal zone vigilance, ecosystem monitoring, and water resources.[46] BİLSAT-1 has already fulfilled its mission

42 METU, "BILSAT has fulfilled its mission life time as of August 2006," (n.d.) http://www.bilten.metu.edu.tr/bilsat/en/root/ under "News."

43 TÜBİTAK UZAY, "First satellite designed and built in Turkey: RASAT," (n.d.), http://www.uzay.tubitak.gov.tr/tubitakUzay/en/projects/spaceApplications.php under "Projects: Space Applications."

44 Ibid.

45 TÜBİTAK UZAY, "GÖKTÜRK-2 is in Space," (n.d.), http://www.uzay.tubitak.gov.tr/tubitakUzay/en/newsArchive/gk-2.php under "News Archive."

46 Ibid.

lifetime as of August 2006, but the RASAT, having a 3-year expected mission lifetime and GOKTURK-2, having a 5-year expected mission lifetime are both still operational in orbit as of January 2013.

TÜBİTAK UZAY has two other ongoing projects: GÖKTÜRK-1 and HALE. GÖKTÜRK-1 is another earth observation small satellite with a high resolution electro optic (E/O) payload to provide images of any location in the world for military and civilian applications. GOKTURK-1 provided support to forest control, detection of illegal construction, crop management and disaster monitoring. The plan for GOKTURK-1 operations includes establishing an Assembly, Integration and Test Center which will be used for all future Turkish satellites up to 5 tons in weight.[47] Turkey is also researching a Facility Establishment Project for Electric Propulsion Applications Research and Hall Thruster Development (HALE). Turkey plans to establish a HALE facility for research and development of electric thruster technologies.[48]

Turkish Aerospace Industries Inc. (TAI) has successfully completed the DÖNENCE project which aimed to achieve the capability to produce Control Moment Gyroscopes (CMG's) and Energy Saving Control Moment Gyroscopes (IPAC CMG's).[49] After successful completion of the CMG R&D Development Project in 2010, TAI gained the capability to build European Cooperation for Space Standardization (ECSS) qualified flight ready units, as well as the ability to re-size, develop, manufacture and test CMG's for different missions as needed.[50]

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47 Turkish Airspace Industries (TAI), "GOKTURK-1," (n.d.), https://www.tai.com.tr/en/project/gokturk-1 under "Programs, Space Systems, Co-Development/Production."

48 TÜBİTAK UZAY, "Facility Establishment Project for Electric Propulsion Applications Research and Hall Thruster Development (HALE)," (n.d.), http://www.uzay.tubitak.gov.tr/tubitakUzay/en/projects/spaceApplications.php under "Projects: Space Applications."

49 Turkish Airspace Industries (TAI), "DÖNENCE Program," (n.d.), https://www.tai.com.tr/en/project/donence-program under "Programs, Space Systems, Indigenous Development." (Accessed on January 30, 2013).

50 Ibid.

It is clear that Turkey has been researching different space-based remote sensing capabilities for military and civilian applications dealing with earth observation, environmental control, disaster monitoring, mapping and planning purposes. As discussed in Section 1.2. “Potential Missions for Smallsats/Cubesats,” ISR and remote communications should be considered primary missions while weather observation, environmental observation and disaster monitoring should be considered secondary missions. Comparing Turkey’s current space capabilities with required space capabilities, the biggest gap is in remote communications with 24/7 continuous coverage required over the Turkish Armed Forces area of operations. For this reason, the objective of this thesis is to propose an optimized space-based capability that will “provide continuous communications capability over the Turkish mainland and a wider designated area that includes surrounding seas (The Black Sea, The Aegean Sea and The Mediterranean Sea) as well as significant portions of the neighboring countries’ territories by establishing a constellation of small satellite systems orbiting at LEO.”

II. CONCEPT OF OPERATIONS (CONOPS)

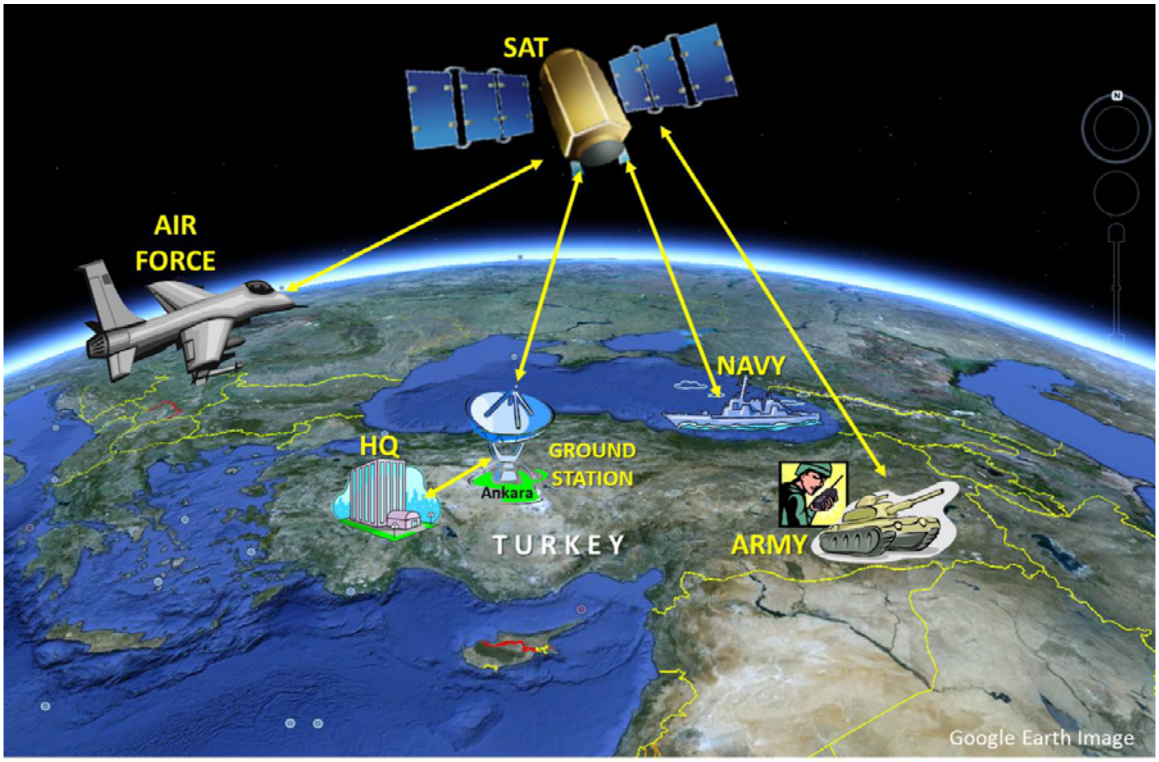

Figure 4. CONOPS layout of satellite constellation.[51]

A. CONOPS OVERVIEW

A constellation of small communications satellites at LEO could provide 24/7 continuous communications capability for Turkish Armed Forces units over Turkish territory and over The Black Sea, Aegean Sea and Mediterranean Sea, especially over the mountainous eastern part of the country and surrounding seas; and such a constellation might also improve communications capabilities for NATO forces and units operating in the region.

The constellation of satellites would be used for relay of communications signals received from a unit or platform in the region to another unit or platform in the region. For instance, an aircraft flying over the Mediterranean Sea may send

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[51] Google Earth image is used in Microsoft Office 2010 PowerPoint program to build CONOPS layout in Figure 4, Feb 22, 2013.

data to the satellite and the satellite would relay that data to the operations center located in inland Turkey. A second example is a ship sailing in the Black Sea communicating with an aircraft flying over the Aegean Sea. Therefore, communications payloads on these satellites must have the technical capability to communicate with the existing communications devices of the Turkish Armed Forces on air, sea and land. In order to provide 24/7 continuous coverage over the designated area, the constellation must be optimized to have at least one satellite overhead at all times.

The central ground station of the constellation would be located in Ankara, and would act as the main hub for receiving satellite telemetry and executing command and control operations (see Figure 4). The Golbasi Facility will receive telemetry data from the constellation in order to monitor health and status of the satellites, execute calculations for orbital maintenance, determine the necessary adjustments and send command and control data to perform the appropriate maneuvering required for station keeping. This facility will be the primary operations center for constellation command and control. Additional ground stations could be added to the west of the Golbasi Facility as back-up/secondary operations centers. This way, if the Golbasi Facility misses a communication opportunity with a satellite, when receiving telemetry or transmitting command and control data, there will be a second chance to accomplish a successful connection at the back-up facility. When maintenance operations are scheduled at the primary station, such as software/hardware upgrades, the command and control operations can be executed from the alternate ground station. As Earth is rotating from west to east, it is better to have the alternate operations center to be at the west of the primary one. Turkey can also coordinate an alternate ground station to be located in another NATO country that has a ground station for space communications to the west of Turkey.

A headquarters (HQ) should be established in close proximity to the Golbasi Facility to make decisions on satellite resource allocation and user priority determination. This HQ should include representatives from all agencies

using the system. Any user request for an allocation of a frequency should be made directly to the Golbasi HQ. Requests from Army, Air Force and Naval units and/or platforms and law enforcement units should all be forwarded to the Golbasi HQ in a timely manner, and all user requests should be determined within the HQ. Sharing of information with law enforcement bodies and/or government agencies will also be determined by this HQ. The priority of use for the system will be decided according to the urgency and relation to national security, and all the decisions will be made by the commander on duty at the Golbasi Facility HQ in the name of the Turkish government. The authority should be delegated to the Commander on duty with appropriate documentation where the satellite usage allocation rules are clearly stated. For instance, an infantry battalion facing a terrorist attack at the moment should have a higher priority than a law enforcement body monitoring illegal trafficking at the same time, and this decision should be made by the commander on duty at the Golbasi Facility HQ. Satellites should be able to serve law enforcement bodies' communications needs when permitted in accordance with the urgency and national security priorities. If urgency or national security is not the case, then the priority among the security forces should be Air Force, Navy, Army, Coast Guard, Gendarmerie and then Police forces. This priority line up is based on how fast a response is required by the user depending on the platforms they use. For instance, an aircraft pilot in flight is accepted as a person under stress who needs a very fast response to a request for additional communications capability, and he/she should have a higher priority than a navy's ship or an army's vehicle.

Frequency or electro-magnetic spectrum de-confliction should be prevented before causing interference with previously allocated frequencies. De-confliction should be made by the Turkish Air Force HQ and all the agencies that have access to these satellite systems need to be involved in the frequency de-confliction meetings as well as the other agencies that might be affected by the spectrum change. Each user can submit their individual frequency requests to the de-confliction board, which will be formed under the Turkish Air Force

Headquarters for planning, executing and reporting the de-confliction meetings. The board should first prioritize the user requirements in accordance with the national security priorities of the country, and then prepare the draft frequency allocation plan to be discussed at the de-confliction meeting. The final decision should be made at this meeting with the participation of all decision makers.

B. GENERAL REQUIREMENTS DESCRIPTION

The Republic of Turkey is the main stakeholder, while security forces (Turkish Armed Forces and law enforcement bodies of Turkey), NATO, other government agencies and the national space industry are secondary stakeholders. Considering the whole country as a main stakeholder, its first priority requirement is to maintain and empower the security of its people and the region. From this perspective, increasing the capabilities of Turkish security forces, efficiently protecting Turkish borders, having competent and capable security forces in the Turkish region and having a better communications capability over Turkish territory and beyond would all help improve Turkey's security. The second priority requirement is to attain the most advanced technological level to increase the wealth of the Turkish people and become one of the most modernized societies in the world. In order to obtain such a goal, The Republic of Turkey is required to achieve a level of independence in developing and producing space technology and thereby benefitting from its advantages. Continuously investing in space industry and manpower training, developing rapid technology projects related to space, providing technology transfers and increasing space-based capabilities would help Turkey to achieve an independent space capability. For the problem defined in this thesis, it is clear that solving the communications needs of its security forces with a space-based capability would both empower the security of the country and fulfill a big step in the Turkish goal of achieving an independent space capability.

Other stakeholders' requirements can be defined as:

- The Turkish Armed Forces, law enforcement bodies and other government agencies need to gain continuous, effective and reliable communications capability for their units over the territories in which they operate and are responsible for.
- The Turkish space industry needs to be supported by the government with more space projects and technology transfers that provide technology and capability improvements.

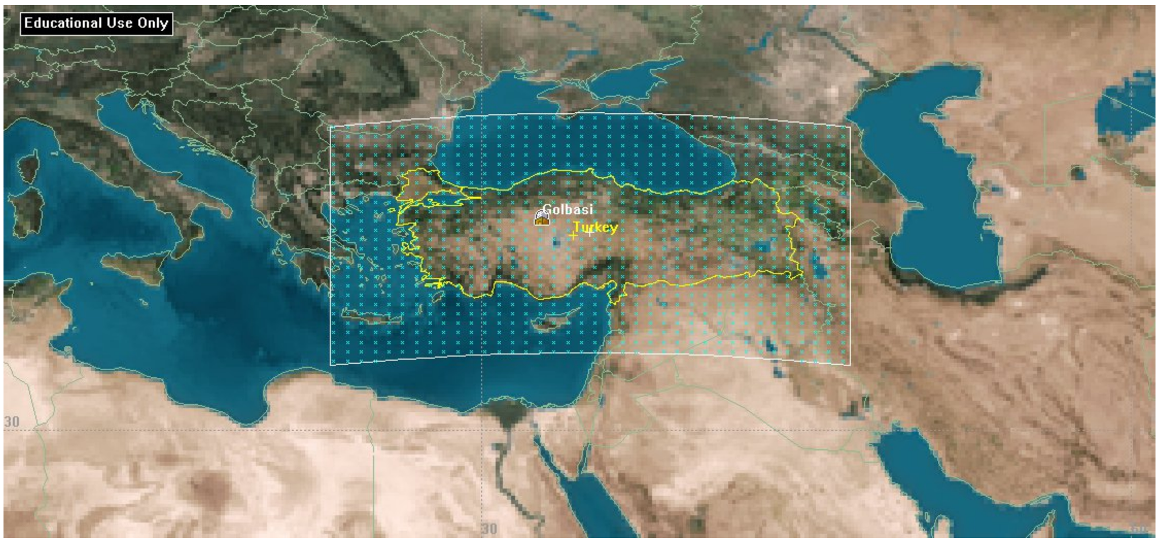

Figure 5. Coverage area defined for analysis.[52]

The constellation of satellites is required to continuously cover the area in which Turkish Armed Forces' platforms, units and/or facilities operate. The area considered in this analysis includes the whole Turkish territory, the seas surrounding it and some territories beyond the country's borders in the eastern part, especially to be used for executing operations against PKK/Kongra-Gel terrorist groups that are located in Northern Iraq. For easier and more effective analysis purposes in this study, a wider and more clearly identified region is defined as the coverage area between the coordinates 44E-23N, 33E-23N, 33E-47N and 44E-46N (see Figure 5).

[52] From Analytical Graphics Inc.'s Systems Tool Kit Software, Version 9.2.2, 2011.

C. MISSION DESCRIPTION

The mission of this space system is to provide effective, reliable and continuous Ultra High Frequency (UHF, 300 MHz-3 GHz) voice and data communications capability over the territories of The Republic of Turkey and the surrounding seas, Black Sea, Marmara Sea, Aegean Sea and Mediterranean Sea for serving the Turkish Armed Forces. Under this defined mission, there will be several sub-missions delegated to the users. The Turkish Air Force HQ will be responsible for allocating frequency use and leading the satellite operations including telemetry, command and control of the constellation. TÜBİTAK UZAY and METU academic personnel will be assisting the Air Force in operating the bus and the payloads. The Golbasi HQ will be main center for these operations. The precedence of the users should be:

– Office of the President of Turkey,
– Office of the Prime Minister,
– Ministry of Defense, Turkish General Staff, Turkish Air Force, Turkish Navy, Turkish Army,
– Ministry of Interior, Turkish Coast Guard, Turkish Gendarmerie, Turkish Police,
– NATO,
– Other government agencies, TÜBİTAK UZAY, METU and other universities.

D. SPACE ARCHITECTURE DESCRIPTION

A number of small satellites will form a constellation orbiting at LEO with the same technical capabilities but different orbital parameters in order to provide 24/7 coverage of the region as shown in Figure 5. The constellation is formed using the Walker Delta design. Satellites in a Walker Delta constellation are

distributed evenly in different orbital planes at the same inclination.[53] The ascending nodes of orbital planes are uniformly distributed around the equator, while satellites are distributed uniformly in those orbital planes.[54] Walker constellations are generally used for providing global coverage as they form a completely symmetrical constellation in longitude, however they may be used for regional coverage for a limited number of possibilities which is also advantageous for optimization calculations and simulations.[55] In this thesis, constellations between 10 and 50 satellites were analyzed at three different altitudes (900 km, 700 km and 500 km) in the LEO region. The goal was to minimize the number of satellites and then minimize the number of planes, while achieving continuous coverage over the defined area.

E. SPACE SEGMENT

Each small satellite in the constellation will have same technical capabilities. These capabilities should be determined in accordance with the current communications devices that the users have in their inventory. In order to communicate with all the facilities, units and platforms of the Turkish Armed Forces, the communications payload on the satellites should have similar technical capabilities to the systems employed by the various users. The satellites will also have cross-link capability to ensure the ground users stay connected when the satellite being used passes out of range. The handover process between satellites is a necessary capability so that users are not cut off every time a satellite passes out of range. Each satellite should contain multiple “bent pipe” transponders, spot beam antennas pointed toward the Earth, and inter-satellite link antennas pointed toward each of three adjacent satellites (assuming there are two planes) to allow for interconnection for the transport of

53 Douglas J. Pegher and Jason A. Parish, “Optimizing coverage and revisit time in sparse military satellite constellations: a comparison of traditional approaches and genetic algorithms” (master’s thesis, Naval Postgraduate School, 2004).

54 Ibid.

55 Ibid.

real-time voice and data services.[56] The satellites should also downlink telemetry data to the Ground Station in Ankara as they pass by.

Since the real-world data and more reliable calculations were not available until this thesis was populated, a set of default values in the STK program is used to form a generic technical capability for each satellite in the constellations examined in this thesis. Therefore, the results of the analysis should be considered in view of these generic satellite properties. Since a link analysis is excluded from the scope of this thesis, using the default payload specifications will not have any effect on our results, however, it should be noted that such a payload cannot be integrated on a small satellite system in reality. Therefore, the payload specifications should be reconsidered when a detailed link analysis is executed in future follow on research.

F. GROUND SEGMENT

The "Golbasi Facility" is used as the only ground station in this scenario (see Figure 4). It represents the real-world Golbasi Facility in Ankara, the capital city of Turkey. It is located very close to the center of the Turkish territories. This facility is inserted from the pre-installed facility database of the STK program. No changes have been made to the default values; nor has an antenna been defined for this facility. Only a basic 5 to 355 degrees azimuth angle limitation has been made as a constraint to simulate the obstruction caused by higher objects and/or terrain. The antennas on each satellite are accepted to have successful links when they are in line-of-sight of the facility, when the azimuth angle is between 5 degrees to 355 degrees. The facilities and/or ground systems of the model can be populated in the STK program according to the real-world systems in the Turkish Armed Forces inventory; however, this portion is left as future work for further studies.

Theoretically, all ground facilities and vehicles including flying or sailing platforms should be able to communicate with these communications satellites. A

[56] Federal Communications Commission, Public Notice, July 22, 1997.

parabolic antenna with one meter diameter should be the maximum size for most of these systems. Some specific platforms like an aircraft, UAV, small size boat or an infantryman's handheld device should also be able to communicate with the satellites even with a dipole antenna. When we consider the antenna size of an IRIDIUM satellite phone, communications with such an antenna are achievable with today's technology.

The calculations for continuous coverage are accomplished by analyzing the satellite accesses to the coverage area defined with the satisfaction condition of "at least one satellite access to the area" granted. The current covered portion of the area is also calculated by using the appropriate report manager tools provided by the STK program.

G. LINK SEGMENT

All of the satellites in the constellation have the same specifications as stated in Table-1, but these specifications are representative; in reality, the analysis should be performed by using the specifications of current user systems. As shown in Figure 4, the satellites in the constellation will communicate with the air, ground and naval units and platforms via these communications payloads. A one meter parabolic antenna with 55% efficiency is dedicated to both receive and transmit communications signals, as well as to handle the telemetry and control signals to operate the satellite in its orbit. The antenna is linked to a sensor which enables targeting of the antenna towards the coverage area when it comes into line of sight. The frequency for receiver and transmitter is set to 1 GHz with a 40 MHz bandwidth, which is basically the frequency template in the STK program. The default values of the STK are kept as is, such as the power of the transmitter on the satellites (30 dBW), antenna to LNA line loss, LNA gain and LNA to receiver gain loss (0 dB) and the noise temperature (constant at 290 K).

Generic Satellite Communications Equipment Properties		
Antenna	Type:	Parabolic antenna
	Size:	1 meter diameter
	Frequency:	1 GHz
	Efficiency:	55%
	Main-Lobe Gain:	41.0376 dB
	Back-Lobe Gain:	-30 dB
Transmitter	Frequency:	1 GHz
	Power:	30 dBW
Receiver	Frequency:	1 GHz
	Power:	30 dBW
	Antenna to LNA Line Loss:	0 dB
	LNA Gain:	0 dB
	LNA to Receiver Gain Loss:	0 dB
	Noise Temperature	290 K (constant)
	Bandwidth	40 MHz (symmetric)
Sensor	Targeted to	Larger Area (Target)

Table 1. Specifications of communications systems on each satellite.

Time Division Multiple Access (TDMA) processing will be used for multiplexing many users with several satellites. The satellite usage will be allocated to the users by time division from each other, and the Joint HQ at the Golbasi Facility will be in charge of allocating the time. Like many military satellite communication systems using TDMA, this kind of multiplexing would be a better solution for the Turkish Armed Forces' needs at this early stage of developing a space-based communications capability.

III. OPTIMIZATION WITH STK

A. ANALYSIS

The goal was to minimize the number of satellites and then minimize the number of planes, while achieving continuous coverage over the defined area by changing altitude, number of planes, number of satellites per plane, inclination, Inter-Plane Spacing and Right Ascension of the Ascending Node (RAAN) values for the walker delta distribution.

Calculations started with one satellite in one plane at a given altitude to find the period, revisit time and the gaps in daily coverage. Next, several satellites in several planes were simulated at different variations of inclination. The inclination drives each satellite's ground track and determines the latitudes to be accessed by the constellation.[57] If a satellite mission is required to access latitudes plus and minus 70 degrees, then the inclination value should be at or very near 70 degrees.[58] Following that theory, inclinations between 35 and 45 degrees were investigated as Turkey's latitudes are between 36 and 42 degrees north. Interestingly, the inclinations between 45 and 60 degrees were better than those between 35 to 45 degrees. As the Walker Delta Constellation is designed for global coverage, the theory works for the global coverage. However, for achieving better coverage of Turkey which is at Northern Hemisphere, inclination values greater than its northern-most latitude (42 degrees north) worked better.

Generally, all constellation designs seek to minimize the number of orbital planes while achieving the coverage requirements.[59] A higher number of planes provide a more flexible constellation, but the cost of launching and maneuvering

[57] Analytical Graphics Inc. (AGI), "Laboratory Mission 8: Remote Sensing and Constellation Design," May 5, 2006, www.agi.com/downloads/corporate/partners/edu/astro310/stkLabManual062906/Astro310_Mission8.doc under "Class Notes."

[58] Ibid.

[59] Ibid.

satellites into multiple planes can be expensive.[60] When satellite size and launch vehicle performance allow, the satellites on the same plane can be placed into their orbit by one launch vehicle, which reduces the propellant required for orbital insertion.[61] Therefore, this study aimed at achieving not only the minimum number of satellites, but also the minimum number of planes. Different variations of inclination at the same altitude have been simulated with different numbers of planes and different numbers of satellites per plane. Since regional coverage is essential for the study, a minimum of two planes with four satellites was the starting point for the simulations. Following that, the number of satellites per plane and the number of planes are increased to achieve better coverage. Increasing the number of satellites in a plane decreases the revisit time over a target on the Earth's surface and increases the daily coverage value, which was used as the measure for achieving continuous coverage. The daily coverage value is calculated by the STK Reports and Graphics tool by finding the percentage of the time covered over the total time in a day. If the daily coverage value is 100%, then that means the area is covered continuously for 24 hours. If a simulation is run for a month and average daily coverage is 100% for the whole month, it means that 24/7 continuous coverage is achieved.

Walker Delta Constellations were simulated by the STK9 Walker Delta Tool. After creating the template satellite in the constellation, a Walker Delta is constellation formed in STK9 by entering the number of satellites per plane, the number of planes, the inter-plane spacing and the RAAN values. Inter-plane spacing is selected as either 0 or 1, meaning that an inter-plane spacing should be applied or not applied. Setting the inter-plane spacing as 1 staggers the satellites in the defined number of orbital planes, and setting it as 0 would line up the arguments of latitude of the satellites in the defined number of planes.[62] In this study, inter-plane spacing was set to 1 to give better coverage in general. A

[60] Ibid.

[61] Ibid.

[62] Ibid.

Walker Constellation containing *t* number of satellites are evenly divided among *p* number of orbital planes with *s* number of satellites in each ($t = p * s$).[63] The orbital planes are evenly spaced in RAAN between 0 and 360 degrees, if the RAAN value for the constellation is selected to be 360 degrees.[64] For covering the area continuously, it is better to set RAAN to be 360 degrees. This way the satellites in the same orbital plane are distributed evenly within that plane, and the revisit times in that plane will be the same for all. Different RAAN values can be set for covering the target area for specific time intervals (daytime only, night time only, or for a defined time interval). In this study, the RAAN value was set to 360 degrees at all times.

Similar simulations were then experimented with at different altitudes. Higher altitudes imply better coverage for a given instrument, but higher altitudes must be balanced with pointing stability requirements for attitude control and signal-to-noise requirements for communications.[65] The higher the altitude, the greater the distance between the transmitter and receiver, and therefore, the greater the free space (r^2) loss. Since the slant range provides the actual distance between the receiver and transmitter in a link, looking at a slant angle versus nadir will increase the effective range even more, further increasing the r^2 loss. Looking at a slant angle will also increase the amount of atmosphere the communication signal encounters, which increases the atmospheric loss and decreases the signal to noise ratio of the link.

The simulation of this study has only one constraint defined concerning the slant range, which is the 5 degree minimum elevation angle requirement. This way, the curvature of the Earth's surface is mostly accounted for; however a maximum range value has not been defined as a constraint, since a detailed link analysis was not an issue of concern in this thesis. For future studies, the maximum range for each case should actually be defined by the altitude of the

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[63] Ibid.

[64] Ibid.

[65] Ibid.

satellite and the minimum elevation angle. Lastly, each variation of the simulation ran for a month (1–31 December 2012) to obtain daily coverage values over a monthly time period. An average percentage for a month was calculated with this data. Monthly averages of 100% were selected from the simulations as an indication of successful 24/7 continuous coverage being achieved.

B. RESULTS

1. First Set of Simulations

The first variation of the Walker Delta constellations were simulated with the initial values of altitude at 900 km and the sensors pointing at the Golbasi Facility on the ground. Table 2 shows the results of 25 different variations experimented within this simulation. The daily coverage Average percentages given in the last column are calculated from daily coverage percentages for 2–30 December 2012. The simulations ran from 1 December 2012 12:00 UTD to 31 December 2012 12:00 UTD (although for only half a day on December 1 and December 31). The monthly average has been calculated for the dates between 2 to 30 December 2012. For the 18 satellites in 2 planes at 900 km altitude and 55 degrees of inclination, the daily coverage values for the whole month (1–31 December 2012) can be seen in Appendix A. With four of the variations, 100% daily coverage is achieved: 18 satellites in two planes at 55 degrees of inclination, 21 satellites in three planes at 52 degrees of inclination, 24 satellites in four planes at 58 degrees of inclination and 35 satellites in five planes at 56 degrees of inclination. The best result is 18 satellites in two planes, which has the minimum number of satellites in the minimum number of planes.

WALKER DELTA - h=900km, sensors targeted to Golbasi Facility, Ankara/TURKEY						
Test #	Number of Planes	Number of satellites per plane	Total Number of satellites	Inclination (degrees)	Inter Plane Spacing (0,1)	Daily Coverage Average for 2–30 Dec 2012 (%)
1	1	1	1	48	0	7.65
2	1	8	8	48	0	50.56
3	2	4	8	48	0	60.17
4	2	4*	7	48	0	52.71
5	1	12	12	90	0	41.25
6	2	6	12	90	0	65.82
7	2	6	12	52	0	89.81
8	2	6	12	52	1	91.92
9	2	6	12	48	1	91.02
10	2	6	12	53	1	91.85
11	2	6	12	51	1	91.88
12	2	8	16	60	1	94.8
13	2	9	18	52	1	95.29
14	2	9	18	55	1	100
15	3	6	18	45	1	97.76
16	3	6	18	52	1	95.96
17	3	6	18	60	1	90.01
18	3	7	21	52	1	100
19	4	5	20	35	1	85.13
20	4	6	24	52	1	99.22
21	4	6	24	70	1	99.42
22	4	6	24	58	1	100
23	5	4	20	52	1	85.38
24	5	7	35	60	1	96.17
25	5	7	35	56	1	100

Table 2. Results for 900 km altitude.

The ground tracks of these 18 satellites are shown in Figure 6 on a world map from STK. Ground tracks show the evenly distributed satellites between 52 degrees north latitude and 52 degrees south latitude. When the satellites on one plane start to move towards the Southern Hemisphere (52 degrees south latitude), the satellites on the other plane start to fly towards the Northern Hemisphere (52 degrees north latitude), and this set-up results in a satellite flying

over the defined coverage area at all times. Nine satellites per plane fulfill the required number of satellites to cover the area continuously for a day.

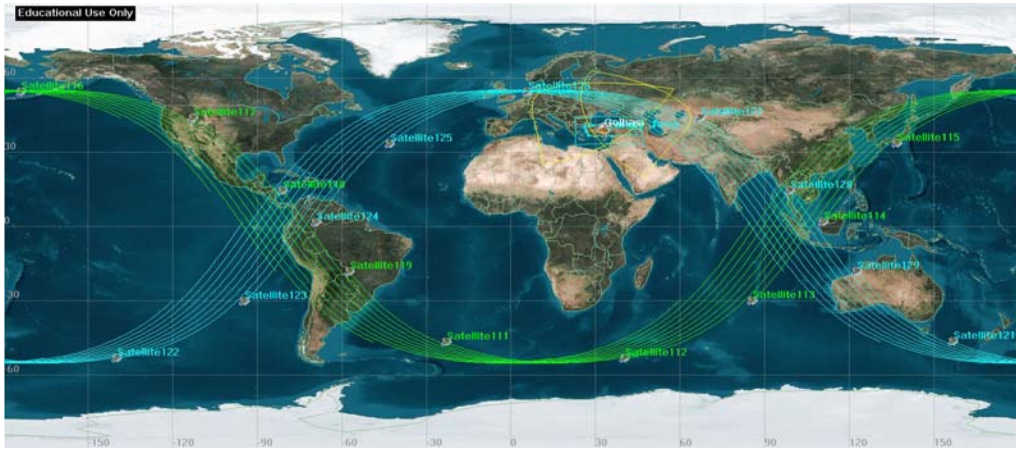

Figure 6. Ground tracks for 18 satellites inclined at 55 degrees in two planes at 900 km altitude.[66]

Two satellites are covering the area simultaneously while passing over the region (Figure 7). The orbital planes and the satellites are shown in 3D view from the Equatorial Plane in Figure 8 and from the North Pole in Figure 9. The coverage maintained by a satellite passing by the region is shown in these figures.

Figure 7. Close up view from the ground tracks.[67]

[66] From Analytical Graphics Inc.’s Systems Tool Kit Software, Version 9.2.2, 2011.

[67] Ibid.

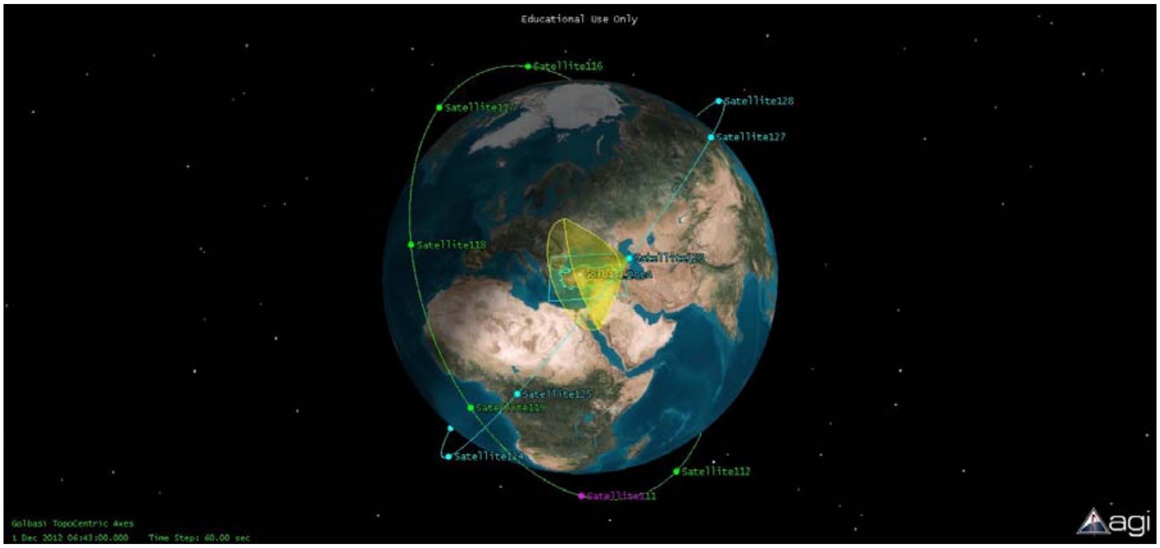

Figure 8. 3D view of the two planes.[68]

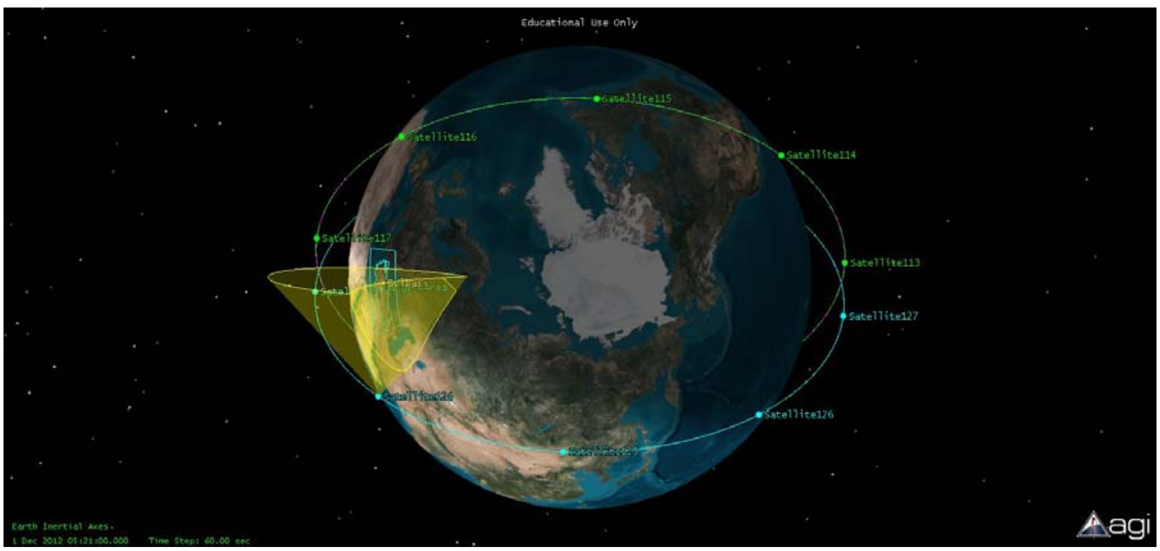

Figure 9. 3D view of the two planes from North Pole.[69]

2. Second Set of Simulations

Similar simulations were conducted for constellations flying at a 700 km LEO. The second set of simulations had only 11 different variations, since better

68 Ibid.

69 Ibid.

predictions were available after the first set of simulations (see Table 3). Similarly, with four of the variations 100% daily coverage is achieved: 20 satellites in two planes at 55 degrees of inclination, 24 satellites in three planes at 52 degrees of inclination, 32 satellites in four planes at 45 degrees of inclination and 35 satellites in five planes at 45 degrees of inclination. The best result is 20 satellites in two planes, which has the minimum number of satellites in the minimum number of planes. The total number of satellites necessary for the 700 km altitude constellation is generally increased compared to the number of satellites necessary for the 900 km altitude constellation. This substantiates the theory of "higher altitude provides greater coverage for the same instruments in a constellation." One satellite flying at a 700 km altitude has a 6.55% daily coverage rate, while the same satellite has a 7.65% daily coverage rate when flying at a 900 km altitude. Therefore, the constellation of 18 satellites in two orbital planes flying at a 900 km altitude provides better coverage than the same constellation at 700 km altitude.

WALKER DELTA - h=700km, sensors targeted to Golbasi Facility, Ankara/TURKEY						
Test #	Number of Planes	Number of satellites per plane	Total Number of satellites	Inclination (deg)	Inter Plane Spacing (0,1)	Daily Coverage % for 2–30 Dec 2012
1	1	1	1	60	1	6.55
2	2	10	20	52	1	99.67
3	2	10	20	60	1	99.1
4	2	10	20	55	1	100
5	3	7	21	58	1	88.76
6	3	7	21	52	1	95.69
7	3	8	24	52	1	100
8	4	7	28	45	1	99.93
9	4	8	32	45	1	100
10	5	6	30	45	1	90.71
11	5	7	35	45	1	100

Table 3. Results for 700 km altitude.

3. Third Set of Simulations

The final set of simulations examined a variety of constellations flying at a 500 km altitude. Table 4 shows the results for 13 different variations at this altitude. For three of the variations, 100% daily coverage is achieved: 30 satellites in three planes at 52 degrees of inclination, 32 satellites in four planes at 58 degrees of inclination and 35 satellites in five planes at 52 degrees of inclination. Only one variation has 99.99% maximum daily coverage: 28 satellites in two planes at 58 degrees of inclination. The best result is 30 satellites in three planes, which has the minimum number of satellites and minimum number of planes for this altitude. The total number of satellites necessary for the 500 km altitude constellation is generally increased compared to the number of satellites necessary for the 900 km altitude and 700 km altitude constellations. At an altitude of 500 km, the minimum number of total satellites increased, as well as the minimum number of planes. Continuous coverage can be achieved with two plane constellations at a 900 km altitude and a 700 km altitude, but a constellation with three planes is required at a 500 km altitude. Therefore, the constellation of 18 satellites in two orbits flying at 900 km altitude is better than the results for the 700 km and 500 km altitudes.

WALKER DELTA - h=500km, sensors targeted to Golbasi Facility, Ankara/TURKEY						
Test #	**Number of Planes**	**Number of satellites per plane**	**Total Number of satellites**	**Inclination (deg)**	**Inter Plane Spacing (0,1)**	**Daily Coverage % for 2–30 Dec 2012**
1	1	1	1	60	1	4.94
2	2	10	20	55	1	95.35
3	2	11	22	55	1	97.31
4	2	12	24	55	1	98.01
5	2	13	26	56	1	99.49
6	2	14	28	58	1	99.994
7	2	14	28	58	0	99.998
8	3	9	27	52	1	98.46
9	3	10	30	52	1	100
10	4	8	32	55	1	99.99
11	4	8	32	58	1	100
12	5	7	35	55	1	99.36
13	5	7	35	52	1	100

Table 4. Results for 500 km altitude.

IV. CONCLUSION

A. SOLUTION

This study for researching better communications coverage over the entire Turkish territory and most of the seas surrounding the country has been accomplished to serve warfighter’s needs for fighting against terrorism and empowering security in the region. A solution based on acquiring space capability is defined in the “1.A. Why Space” section to address the problem, while providing newer technologies and capabilities for the country in addition. Based on the solution defined, continuous coverage over Turkish territory and over the surrounding seas has been examined by simulating and analyzing a variety of communications satellite constellations with STK software. 15 different solutions with 100% daily coverage over the region have been found among 49 variations that were simulated at three different altitudes. Starting from a set of simulations for a 900 km altitude and then repeating the simulations at 700 km and 500 km altitudes, the results are compared. Verifying the theory of “higher altitude provides greater area covered for same instrument used,” the results for the 900 km altitude were better than those for the 700 km and 500 altitudes respectively. Following the goal to minimize both the number of satellites and planes, 18 satellites in two planes at 55 degrees of inclination and an altitude of 900 km is the best solution among all 15 solutions fulfilling the continuous coverage requirement.

Overall, the results of this thesis will provide useful information by defining the optimal set of satellites to satisfy Turkish Armed Forces’ communications needs over defined territory in possible future projects. It will establish the basic level of planning needs for such missions and provide initial feasibility research as well.

B. LIMITATIONS AND FUTURE WORK

Simulations were accomplished with limitations in the space segment, link segment, digital terrain elevation data analysis, constellation selection, launch options and cost analysis.

In the space segment, due to unavailability of data, detailed specifications for the satellite communications payload could not be modeled, and the STK default data was used instead. Developing detailed information on the satellite communications payload will provide more realistic data for constellation optimization.

Since the current communications frequencies used by the Turkish Armed Forces are classified and could not be used during the research, no link analysis was conducted in this study. Defining the exact specific frequency range to be used, selection of the modulation type, comparison of different multiplexing techniques, and calculation of atmospheric loss, rain attenuation and interferences were all excluded. In fact, it is true that "the higher altitude provides better coverage with same instruments"; however, the quality of the link decreases as the range increases since the atmospheric attenuation increases. These calculations should be included to further refine the constellation optimization calculations.

The coverage is simulated with the antenna pointing at the Golbasi Ground Facility located at 39.7904 degrees North latitude and 32.809 degrees East longitude, and the daily coverage percentages are calculated by the duration of successful links between satellites in the constellation and this facility. Since Digital Terrain Elevation Data (DTED) was not available, the amount and percentage of the actual area coverage is excluded. Considering that the problem in the mountainous eastern part of the country is highly related to the elevation of the terrain, DTED data should be acquired and constellation optimization simulations should be executed with DTED data included in the calculations.

The Walker Delta was the only constellation type used in this simulation. Although it is the most common type of constellation used, different types of constellations, including a custom one with elliptical orbits, may increase the coverage percentage while decreasing the required number of satellites and should be considered in further research.

The launch options for establishing the constellation are excluded in the study. The feasibility of maintaining the orbital insertion for evenly distributed satellites throughout the 360 degrees of RAAN within the constellation should be analyzed with current launch capabilities and launch sites along with cost comparison data for launching different constellation configurations.

A detailed cost analysis has also been excluded as there are many uncertainties at this early stage of the project. Since the spacecraft solution is assumed to use Commercial Off-the-Shelf (COTS) parts and devices, it would be easier to execute an initial cost analysis once the satellite properties are determined and clarified.

All the results stated in the thesis are based on these limitations explained, and these areas are recommended for all future studies on the same subject.

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APPENDIX. DAILY COVERAGE DATA FOR 1–31 DECEMBER 2012[70]

ObjectCoverage-Ox1475C680: DailyCoverage	
Start 12/1/2012 12:00	**Stop** 12/31/2012 12:00
Date (UTCG)	**Percent Time Covered**
12/1/2012 0:00	50
12/2/2012 0:00	100
12/3/2012 0:00	100
12/4/2012 0:00	100
12/5/2012 0:00	100
12/6/2012 0:00	100
12/7/2012 0:00	100
12/8/2012 0:00	100
12/9/2012 0:00	100
12/10/2012 0:00	100
12/11/2012 0:00	100
12/12/2012 0:00	100
12/13/2012 0:00	100
12/14/2012 0:00	100
12/15/2012 0:00	100
12/16/2012 0:00	100
12/17/2012 0:00	100
12/18/2012 0:00	100
12/19/2012 0:00	100
12/20/2012 0:00	100
12/21/2012 0:00	100
12/22/2012 0:00	100
12/23/2012 0:00	100
12/24/2012 0:00	100
12/25/2012 0:00	100
12/26/2012 0:00	100
12/27/2012 0:00	100
12/28/2012 0:00	100
12/29/2012 0:00	100
12/30/2012 0:00	100
12/31/2012 0:00	50
Average 2–30 DEC:	100

[70] Walker Delta Constellation parameters: 18 satellites in 2 planes (9 satellites per plane), Inter Plane Spacing=1, RAAN is 360 degrees, altitude is 900 km (LEO), inclination is 55 degrees, eccentricity is zero and sensor pointing is set to targeted.

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